ELSEVIER

Nuclear Instruments and Methods in Physics Research A 442 (2000) 238–243

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.nl/locate/nima

High-resolution detectors in nuclear spectroscopy

J. Gerl

GSI, Gesellschaft für Schwerionenforschung, Postfach 11 05 52, D-64220 Darmstadt, Germany

Abstract

The sensitivity of gamma-ray spectrometers for nuclear structure studies has improved by two to three orders of magnitude within the last 10 years. This impressive progress is based on larger HPGe crystals, composition of several crystals into a detection unit and electrical segmentation of the detector contacts. Current development projects are concentrating on optimizing the solid angle coverage of detector arrays to further increase the efficiency and on increasing the effective granularity of the detectors. The latter requires further segmentation and gamma-hit position determination by signal-shape analysis. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Gamma-ray detection; Segmented Ge detectors; Pulse-shape analysis

1. Introduction

The continuous development of γ-ray detectors within the last 10 years enabled significant progress in nuclear structure physics. Typically, each new generation of γ-ray spectrometers [1,2] improved the detection sensitivity by an order of magnitude. Cold atomic nuclei in or near the valley of stability have been studied extensively by decay spectroscopy, inelastic excitation and nuclear reactions. Their structure is now rather well investigated and understood in terms of effective interactions. However, the extrapolation of our knowledge to hitherto unknown areas of nuclear parameter space as to high angular momenta, to superheavy nuclei or to extreme proton-to-neutron ratios is strongly limited by the effective nature of our models. The investigation of nuclei under these extreme conditions is therefore the main object of future nuclear structure research. For that purpose several new radioactive ion beam accelerator facilities are being realized all over the world together with the next generation of γ-ray arrays.

The power of a γ-spectrometer is characterized by its ability to detect specific γ-rays from a nuclear reaction and to discriminate them against background radiation. Therefore, the total full-energy detection efficiency, P_{ph}, for energies in the range $E_\gamma = 100$ keV–10 MeV must be maximized. The energy resolution ΔE_γ, affected by the Doppler effect associated with fast moving γ-emitting nuclei, must be minimized. Finally, the peak-to-total ratio P/T must be maximized taking into account escaping γ-rays from Compton scattering or pair production in the detector, uncorrelated background radiation and multiple hits from nuclear events with high γ-multiplicity ($M_\gamma \approx 30$). This contribution describes the concepts employed in the development of γ-spectrometers to fulfill these criteria. For the foreseeable future only hyperpure Ge seems

E-mail address: j.gerl@gsi.de (J. Gerl)

PII: S0168-9002(99)01227-9

to be a suitable material therefore the discussion concentrates on Ge detectors.

2. Detector response

In order to optimize the intrinsic full-energy efficiency ε_{ph} of a Ge detector two conditions have to be fulfilled: (i) the length of the detector must be sufficient to cause an interaction with the incoming γ-rays and (ii) its diameter – especially in the back region – must be large enough to stop the Compton-scattered γ-rays. Monte-Carlo simulations were performed to determine the optimum ratio between length and diameter l/d. Assuming a cylindrical detector of volume $V \geq 1000$ cm^3 the maximum efficiency is obtained at $l/d \approx 1$ as shown in Fig. 1.

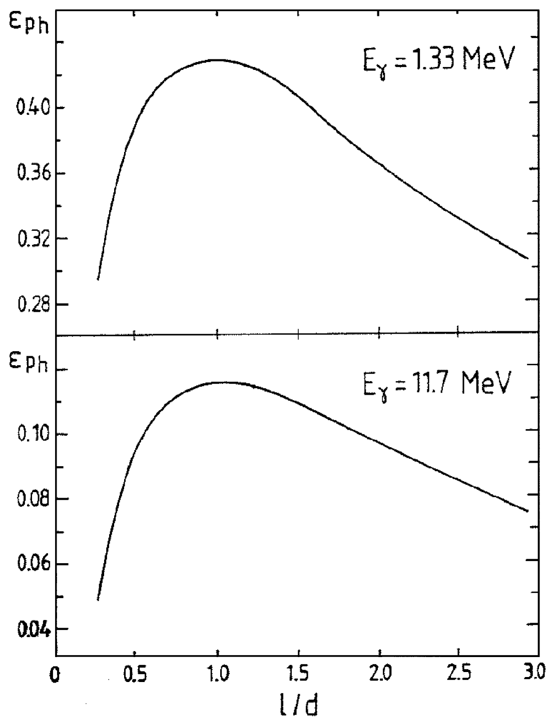

Fig. 1. Photopeak efficiency as function of the ratio between length and diameter l/d of an idealized cylindrical Ge detector. A volume of 2000 cm^3 was assumed, approximately matching the total active volume of the Super Segmented Clover detector. The simulation calculations using the code GEANT3 [8] are based on a constant solid angle of $\Omega = 0.0136$.

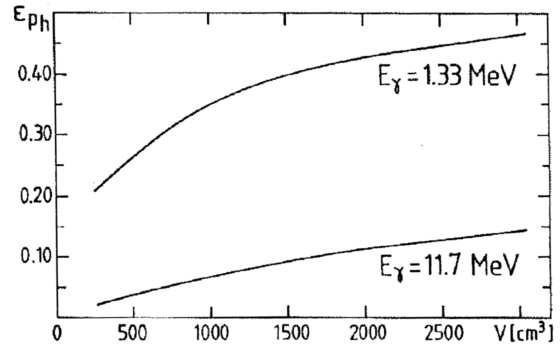

Fig. 2. Photopeak efficiency of an idealized cylindrical Ge detector of equal length and diameter as function of volume. A constant solid angle of $\Omega = 0.0136$ is assumed.

Fig. 2 shows the photopeak efficiency of an idealized cylindrical Ge detector as a function of the Ge volume. Requiring $l/d = 1$ the largest n-type crystal volumes available are about $V \approx 500$ cm^3, corresponding to an efficiency of $\varepsilon_{ph} \approx 0.25$. To further increase the volume and thus the efficiency composite detectors have been developed. They consist of close-packed arrangements of four (Clover detector [3,4]) or seven (Cluster detector [5,6]) crystals. Energies from γ-rays scattered between the crystals are added, which increases the efficiency considerably (see Fig. 5). In the case of the Cluster detector each crystal is housed in a vacuum-tight aluminum capsule to improve the reliability [7]. Detailed simulation calculations showed that the efficiency is increased by as much as 15% by slightly tapering the front edge of the crystals to a length of 2–4 cm.

The P/T-ratio of large single-crystal Ge detectors is 0.2 for a ^{60}Co source. The composite detectors reach values up to $P/T \approx 0.4$. To further improve the response to $P/T \leq 0.7$ the detectors are surrounded with Compton-suppression shields made from BGO. However, the BGO jacket, with a typical thickness of 15–25 mm, covers a large part of the solid angle of a detector unit. Increasing the effective diameter of the Ge detector improves the ratio of active to total solid angle covered by a unit. For the total full-energy efficiency of a 4π array the gain in this ratio by employing composite detectors is, in fact, even more important than the gain in intrinsic efficiency.

3. Spectrometer granularity

There are two reasons to demand high granularity N_{gr} for a γ-spectrometer. One is the reduction of multiple hits in events with high γ-multiplicity, e.g. for $M_\gamma = 30$ the isolated hit probability increases from $P_i = 0.56$ for detector elements covering a solid angle of $\Omega = 0.02$ to $P_i = 0.94$ for $\Omega = 0.002$. The second reason is the Doppler broadening of the γ-lines due to the recoil velocity of the γ-emitting nucleus. In experiments with relativistic radioactive ions velocities up to $v/c = 0.6$ may be expected.

As an example Fig. 3 shows the broadening of the 547.5 keV line from the γ-decay of ^{197}Au nuclei moving at $v/c = 0.093$. The composite detector of the super segmented clover-type [3,13] (see below) used in an experiment performed at GSI Darmstadt [9] covered an active solid angle of $\Omega \approx 0.06$ and was placed at 90° with respect to the flight direction of the ^{197}Au nuclei. Taking separate spectra for the four crystals of this detector reduced the line width from 34 to 17 keV. To further increase the granularity the electrode(s) of a Ge detector can be electrically segmented. The detector in the example has a fourfold segmentation of each crystal. This reduces the Doppler broadening to 7–9 keV in case of only one responding segment, respectively, to 8–10 keV for two neighbouring segments (green = parallel,

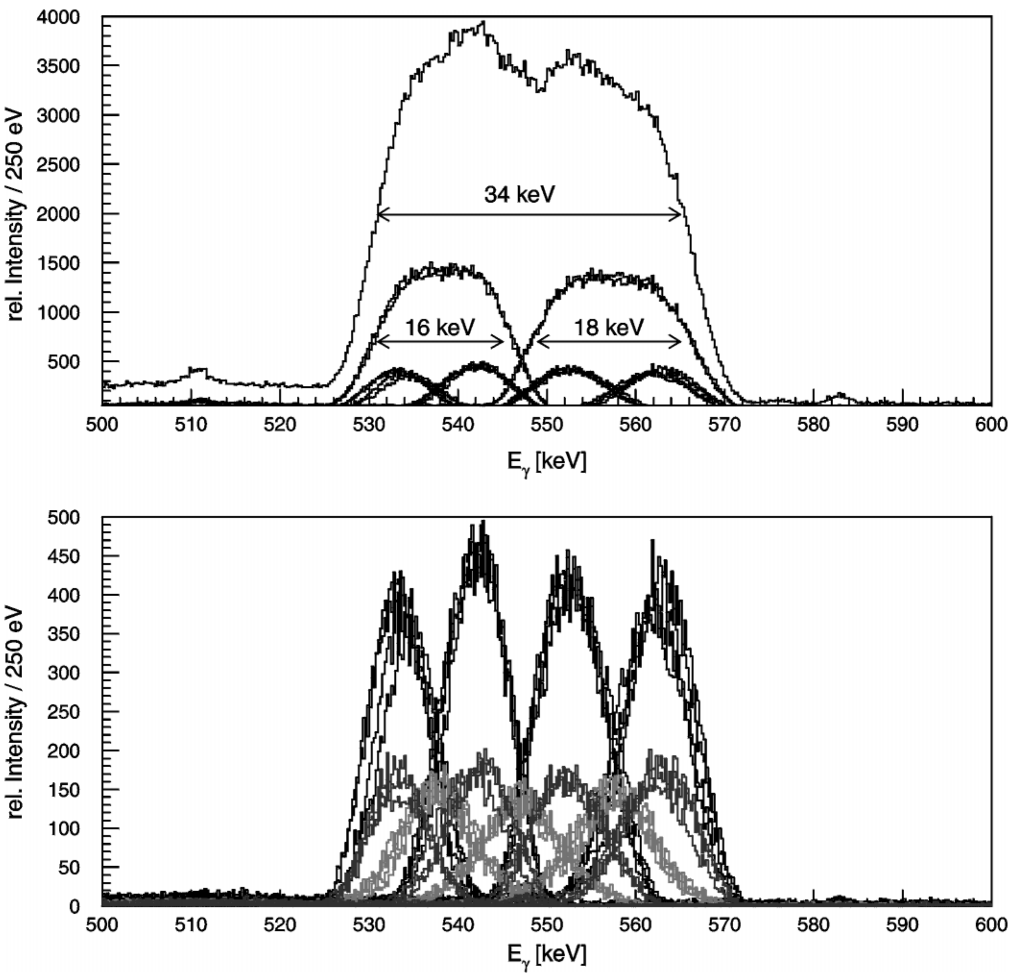

Fig. 3. Overlay of the Doppler broadened line shape of the 547.5 keV ^{197}Au line (see text).

blue = perpendicular to the moving nuclei). Similar results were also obtained for other segmented detectors [10]. This demonstrates that composite detectors with additional contact segmentation are a proper concept to increase the granularity of γ-arrays.

4. Ge detectors and arrays for nuclear structure studies

The evolution of detector technology in the 1990s in Europe brought about three generations of powerful 4π Ge arrays. The first generation was still based on large tapered single crystal detectors. Two arrays were built: GASP [11] ($P_{ph} \approx 0.03$, $N_{gr} = 40$) at LNL Legnaro and Eurogam I [12] ($P_{ph} \approx 0.04$, $N_{gr} = 45$) at DRAL Daresbury. In the next generation, composite Clover detectors were used for the first time. One array was built: Eurogam II [12] ($P_{ph} \approx 0.07, N_{gr} = 126$) at IRES Strasbourg. The 4π array Euroball III [14,15], which is operational at IRES Strasbourg, constitutes todays state-of-the-art Ge-based γ-spectrometer. In addition to Clover detectors the use of Cluster detectors allowed to increase the granularity to $N_{gr} = 239$. Therefore, the array is optimal for high-multiplicity applications, the P_{ph} value being "only" ≈ 0.1.

Evolving from the Euroball project segmented Ge detectors are currently being developed: Segmented Cluster and Segmented Clover detectors shall be employed in the Miniball [16] and Exogam [17] array, respectively, dedicated for low-multiplicity applications, in particular, with radioactive beams e.g. at Cern-Isolde Geneva, GSI Darmstadt and Ganil Caen. This application requires optimization of the total photopeak efficiency and a high granularity of the individual detectors to adequately correct for large Doppler effects deteriorating the energy resolution in in-beam experiments. These arrays, which are planned to be available in late 1999, will provide P_{ph} values up to 14% depending on the configuration and granularities of $N_{gr} = 252$, respectively, $N_{gr} = 256$.

The latest Ge array currently being build is the Vega array [13] located at GSI Darmstadt. It will consist of a compact box-like array of four Super

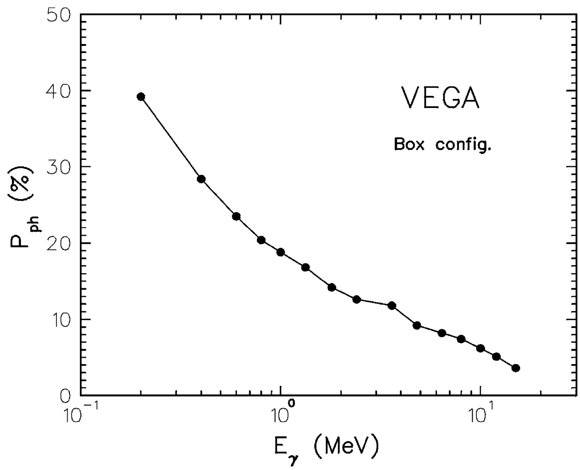

Fig. 4. Total photopeak efficiency P_{ph} as a function of the γ-energy for the Vega array in the compact box-like configuration.

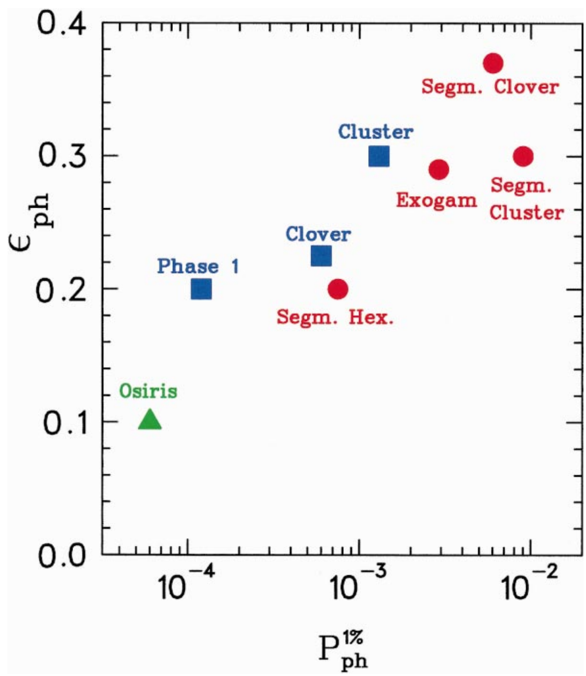

Fig. 5. Related values of intrinsic photopeak efficiency ε_{ph} and maximal total photopeak efficiency $P_{ph}^{1\%}$ for one detector, obtained under the requirement of an energy resolution of 1% for a γ-emitter moving with $v/c = 10\%$ perpendicular to the detector. The triangles corresponds to a typical pre-Euroball detector, squares mark the various Euroball detector types and circles correspond to newly developed segmented Ge detectors.

Segmented Clover detectors which have been developed in a collaboration between GSI Darmstadt and the company Eurisys Strasbourg. The Super Segmented Clover consists of four touching Ge crystals composed like a clover leaf. Each crystal is electrically divided into four segments. Due to this arrangement the detector has an excellent polarization sensitivity. The detector consists of Ge crystals with 14 cm length and 7 cm diameter. The total Ge volume obtained thus considerably exceeds all other detector designs. Therefore the largest efficiency, in particular for high γ-ray energies, is achieved as can be seen in Fig. 4.

Fig. 5 shows the improvements in ε_{ph} and the maximally obtainable total photo peak efficiency ($P_{ph}^{1\%}$) for a given energy resolution of $\Delta E_\gamma / E_\gamma = 1\%$, which have been achieved within this decade by realizing new detector concepts. The increase in ε_{ph} is due to larger crystals and the packing of several crystals into one detector unit. Here the optimum is achieved with the Super Segmented Clover. $P_{ph}^{1\%}$ mainly depends on the limitation of the Doppler broadening for a given detector and thus on the effective solid angle. Compared with single-crystal detectors the composite Euroball detectors, where the detector surface is divided

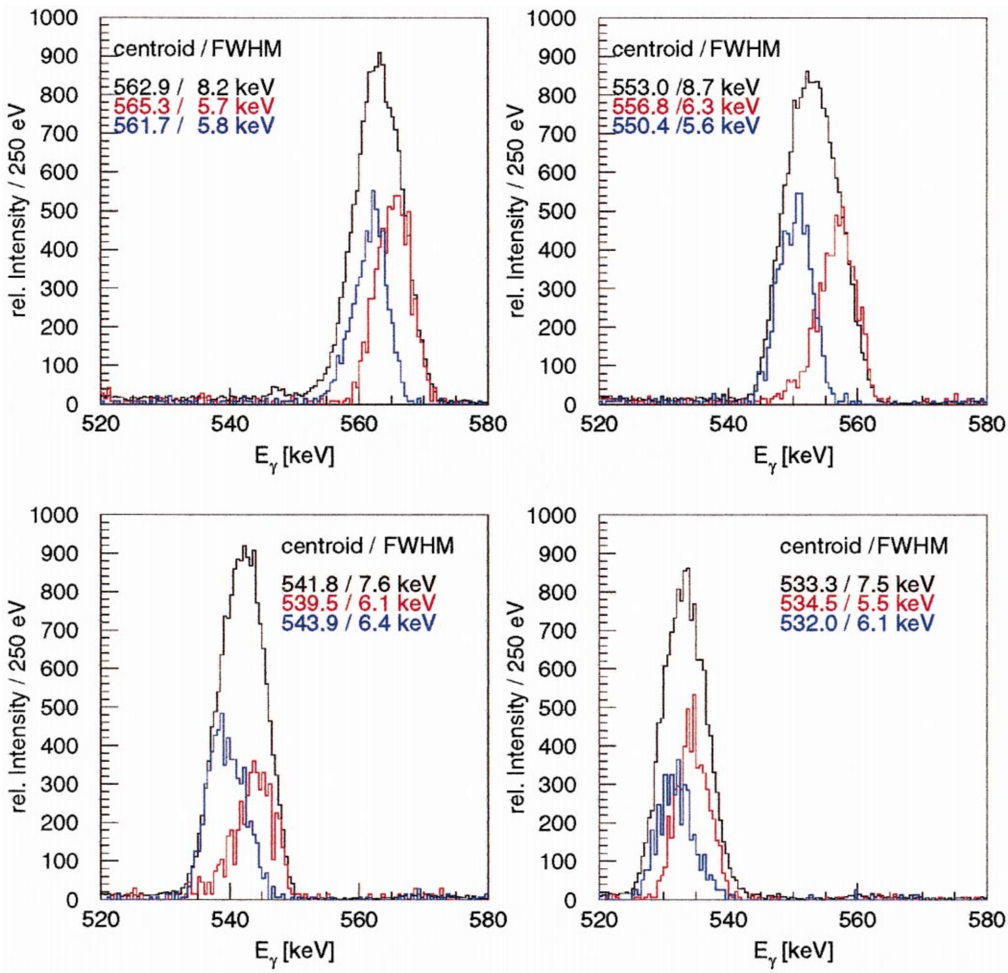

Fig. 6. 547.5 keV line of ^{197}Au for four segments at different scattering angles (black) and examples for line shapes with reduced width (red, blue) obtained by choosing certain interaction positions of the γ-rays through pulse shape analysis.

among several crystals, provide already one order of magnitude higher $P_{ph}^{1\%}$ values. Another order of magnitude is gained by segmentation of the electrical contacts. Here the Segmented Cluster with 42 granuli achieves the best results. This gain in $P_{ph}^{1\%}$ values directly corresponds to the gain in sensitivity to detect subtle nuclear structure effects.

5. Future developments

The next step to further increase the effective granularity is to derive interaction position information from the pulse shape of a detector signal. Recent investigations have shown that a radial position resolution in the order of $\Delta r = 4$–7 mm can be achieved, e.g. by correlating rise time differentials of different parts of the pulse [18] or by determining the steepest slope of the differenciated charge signal [19]. The improvement in the line width employing the former method to correct for the Doppler effect in the experiment described above is shown in Fig. 6. The remaining broadening is in quantitative agreement with the one expected from the uncertainty in the flight direction of the ^{197}Au nuclei.

In the experiment the pulse shape was measured event by event using a f-ADC with 250 MHz sampling frequency. All sampled data were recorded and analyzed off-line. The tremendous data rate to be handled would not permit such a procedure for high event rate multi-detector experiments. Therefore, dedicated electronics coupling f-ADCs to powerful DSPs is currently being developed which will allow on-line pulse-shape analysis to determine the interaction point. Moreover, the new system is meant to completely replace the conventional analog electronics.

In addition to this development line there are attempts to further segment the outer and/or inner contact of a detector to obtain interaction positions in three dimensions. The idea behind that is to reconstruct the trajectory of each γ-ray, i.e. to determine each Compton scattering point until complete absorption. Knowing the complete history of each γ-ray in an event Compton suppression shields are obsolete and a close-packed Ge shell with a total efficiency of $P_{ph} \leq 0.4$ could be realized.

Extrapolating from the major improvements achieved within the last 10 years it may well be that such a futuristic γ-spectrometer could be built within the next decade, offering unprecedented sensitivity for new areas of nuclear structure investigations.

References

[1] C.W. Beausang, J. Simpson, J. Phys. G22 (1996) 527.
[2] R.M. Lieder, in: D.N. Poenaru, W. Greiner (Eds.), Experimental Techniques in Nuclear Physics, Walter de Gruyter, Berlin, 1997.
[3] J. Gerl, K. Vetter, Th.W. Elze, Th. Kröll, H. Xie, Proceedings of the Conference on Physics from Large γ-ray Detector Arrays, Berkeley, LBL 35687, CONF 940888, UC 413, 1994, p. 159.
[4] F.A. Beck, Proceedings of the Conference on Physics from Large γ-ray Detector Arrays, Berkeley, LBL 35687, CONF 940888, UC 413, 1994, p. 154.
[5] J. Eberth and the Euroball collaboration, Proceedings of the Conference on Physics from Large γ-ray Detector Arrays, Berkeley, LBL 35687, CONF 940888, UC 413, 1994, p. 160.
[6] M. Wilhelm, J. Eberth, G. Pascovici, E. Radermacher, H.G. Thomas, P.V. Brentano, H. Prade, R.M. Lieder, Nucl. Instr. and Meth. A 381 (1996) 462.
[7] J. Eberth, H.G. Thomas, P.V. Brentano, R.M. Lieder, H.M. Jäger, H. Kämmerling, M. Berst, D. Gutknecht, R. Henck, Nucl. Instr. and Meth. A 369 (1996) 135.
[8] Geant Detector Description and Simulation Tool, CERN Geneva, 1993.
[9] M. Kaspar, Ph. D. Thesis, University of Frankfurt, 1999.
[10] S.L. Shepard, P.J. Nolan, D.M. Cullen, D.E. Appelbe, J. Simpson, J. Gerl, M. Kaspar, A. Kleinböhl, I. Peter, M. Rejmund, H. Schaffner, Ch. Schlegel, G. de France, Nucl. Instr. and Meth., in press.
[11] C. Rossi-Alvarez, Nucl. Phys. News /bf 3 (3) (1993) 10.
[12] G. de France, J. Simpson, Nucl. Phys. News 7 (1) (1997) 12.
[13] J. Gerl, H. Grawe, E. Roeckl, H.J. Wollersheim, VEGA a proposal for Versatile and Efficient Gamma-detectors, GSI Darmstadt, Report, 1998.
[14] J. Gerl, R.M. Lieder, Euroball III, GSI Darmstadt, Report, 1992.
[15] J. Simpson, Z. Phys. A 358 (1997) 139.
[16] D. Habs, D. Rudolph, P. Thirolf, C. Fischbeck, Ch. Gund, D. Schwalm, J. Eberth, E. Grosse, H. Prade, H. Emling, J. Gerl, R.M. Lieder, P. van Duppen, C. Rossi-Alvarez, H. Pignanelli, Progr. Part. Nucl. Phys. 38 (1997) 1.
[17] Exogam project definition, Ganil Caen, Report, 1997.
[18] T. Kröll, I. Peter, Th. W. Elze, J. Gerl, Th. Happ, M. Kaspar, H. Schaffner, S. Schremmer, R. Schubert, K. Vetter, H.J. Wollersheim, Nucl. Instr. and Meth. A 371 (1996) 489.
[19] L. Pallafox, Ph. D. Thesis, MPI H - V 31, MPI für Kernphysik Heidelberg, 1997.